IOP Publishing European Journal of Physics

Eur. J. Phys. **29** (2008) 33–52 doi:10.1088/0143-0807/29/1/004

# The principle of relativity and the indeterminacy of special relativity

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Received 24 July 2007, in final form 18 October 2007
Published 21 November 2007
Online at stacks.iop.org/EJP/29/33

**Abstract**

This work ends a trilogy devoted to a journey into the foundations of special relativity. The first paper debated the meaning of the constancy of the two-way speed of light and its close relation to the conceptualization of time. The second one addressed the question of the possible constancy of the one-way speed of light and the trivial—but, unfortunately, even now somewhat controversial—question of the compatibility between the assumption of a special system of reference and Einstein's special relativity. The present study deals with the principle of relativity. Its historical evolution is reviewed and a 'weak' formulation is defended. It is emphasized that many assertions usually associated with special relativity, such as the 'relativity of time dilation' and 'relativity of space contraction' are indeed *philosophical statements*, as it has been established already by several authors in the past. Nonetheless, most teachers and scientists still believe nowadays they are implied by the theory and by the group property of the Lorentz transformation. This is by no means so, as it is reviewed and elucidated with the simple example on space contraction. It is argued that the lack of knowledge of the true value of the one-way speed of light in empty space leaves the theory *undetermined*. Einstein's special relativity corresponds to a simple and very elegant solution to this problem, allowing the study of relative motion without any concern with the study of absolute motion, which is considered to be superfluous. However, its standard interpretation is minimalist and even misleading. A large number of researchers have discussed this question, mostly within the *conventionality* of simultaneity thesis. The typical formulation of this thesis provides some new physical insight and points out the problem, but does not solve it. In contrast, it often leads to a labyrinth of difficult language which is herein clarified.

(Some figures in this article are in colour only in the electronic version)

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## 1. Introduction

In 2005, the centennial celebration of Einstein's miraculous year, we have started a reflection on the foundations of special relativity. In our first paper, we have reviewed the strong connection existing between the constancy of the *two-way* speed of light in vacuum, the null result of the Michelson–Morley experiment, and the very notion of time [1]. In particular, we have shown that the postulate of the constancy of the two-way speed of light in vacuum can be derived under three fundamental assumptions related to the conceptualization of time: (i) all good clocks can be used to measure time, independently of the periodic physical phenomena they are built upon; (ii) time is measured in the same way in all inertial frames, i.e., if a particular clock can be used to measure time in the 'rest system', a similar clock can be used to measure time in 'moving' inertial frames; (iii) a limit speed exists in the 'rest system'. As pointed out in [1], the argumentation is very general and has to be true not only within Einstein's special relativity and its 'equivalence' of all inertial frames, but also in the Lorentz–Poincaré scenario of a preferred reference frame.

The compatibility between Einstein's special relativity and the Lorentz–Poincaré view of a preferred reference system experimentally inaccessible was shown to hold in our second article [2]. Although both scenarios manifestly differ in philosophy, it is important to recover John Bell's claim [3] that 'the facts of physics do not oblige us to accept one philosophy rather than the other'.

Alas, this rather trivial statement is still surprising to most scientists at present, or even considered to be plain wrong. It must be conceded that what is said in each formulation seems to be contradictory at first sight. However, as pointed out in [2], this is essentially related to a demanding problem of language. By the use of a correct and precise language, difficulties and paradoxes are immediately avoided. Interpretation problems only arise because *words* are used in a sense that is often not correct under the chosen description. As was stressed in [2], the core of the problem is related to the largely debated question of synchronization of distant clocks. Though, reality is not changed by the choices we make to *describe* it, so it cannot be changed by the particular way in which the clocks have been set.

In our opinion, all scientists, teachers and students should be aware of and ponder over Bell's assertion, as it widens the somewhat narrow view of special relativity often presented in textbooks and scientific papers. The main purpose of our previous work [2] was to demonstrate the formal compatibility between both views and to address the question of the possible constancy of the *one-way* speed of light. Time dilation was used as an example. In this final work, we want to discuss the most difficult issue in the framework of Bell's idea—the *principle of relativity*—that closes our visit to the foundations of special relativity.

The aim of this paper is to debate what does the principle of relativity really mean, by showing how and why the principle of relativity *is* indeed consistent with the ideas of Lorentz and Poincaré. For the sake of the clarity of the exposition, and keeping in mind our purpose, we adopt here at first a *language* close to that of the Lorentz–Poincaré philosophy, as was done in [2]. Nonetheless, until late in the paper, no particular interpretation is adopted, the discussion being kept as general as possible and free of interpretation-dependent assertions. The paper is organized as follows.

Section 2 briefly reviews some of the works from [1, 2], as to make the present paper easier to read. In particular, the inertial-synchronized-Tangherlini (IST) transformation and the notions of the *Einstein speed* and *Lorentzian clocks* are recalled.

A presentation of the historical evolution of the principle of relativity is made in section 3. It is worthwhile to do it in some detail—passing through Galileo, Newton, Poincaré and Einstein—since the principle of relativity is very commonly misinterpreted and ill formulated.

The recovery of a weak formulation is proposed, in the line of the formulations made by Feynman [4].

Section 4 clarifies how the ideas reviewed in section 2 and the analysis of the principle of relativity from section 3 relate to the standard interpretation of special relativity. It is shown that the principle of relativity is often stated with little care in textbooks. Furthermore, a new way to make the role of the Lorentz transformation emerge is pointed out.

The question of different possible interpretations—or philosophies, in John Bell's words—of special relativity is finally addressed in section 5. It is held that the theory is undetermined, as it contains an assumption that has not—and possibly cannot—been tested (related to the value of the one-way speed of light). Einstein's formulation constitutes a simple mathematical solution to this problem. A large number of studies connected with this difficulty were made within the conventionality of simultaneity thesis, which is not really discussed in this paper but it is very briefly addressed in sections 5 and 7.

Space contraction is treated using a simple example in section 6. The presentation is made in some measure in a heterodox way, in order to show explicitly and unambiguously how the symmetry of the Lorentz transformation comes out from the existence of a special reference system.

Finally, section 7 summarizes the main ideas guiding this series of papers, providing material to launch further debate and discussion.

## 2. Einstein speed and the IST transformation

In this section, we review some of the ideas presented and discussed in [1, 2]. Let us start by noting that one decisive step to understand how the assumption of a preferred frame is consistent with the standard interpretation of special relativity is to realize that the latter involves additional assumptions than those required by the experiment. Actually, each of the postulates can be formulated in slightly more general terms, while keeping fully compatible with the observed physical reality.

The postulate of the constancy of the speed of light was discussed in [1, 2]. What is implied by experiment (and by the conceptualization of time from [1]) is the constancy of the *two-way* speed of light in vacuum in all inertial frames, independently of the speed of the source. Additionally, it is assumed that there is (at least) one frame where the *one-way* speed of light in vacuum is the same in all directions of space and equal to $c$, identified with the rest frame. Evidently, this weak formulation of the postulate does not contradict and is entirely consistent with the standard interpretation of special relativity. Herein we keep it and exploit it to its full consequences.

Although the conventionality thesis is only very briefly addressed in sections 5 and 7, it is worth noting that at this point there is no ambiguity in the notion of speed. This one-way speed is *not* a convention. Let us not doubt that when light is emitted from point A to point B it travels from A to B, and it does so with a certain speed. Maybe we do not know the value of this speed. Maybe a convention is needed for practical purposes. Maybe the rest system cannot be identified. All these are different matters with implications of their own. But for now it is simply assumed that there is a system in which the one-way speed of light in vacuum is really $c$ in all directions. In [5], it was shown that the existence of such system is implied by the homogeneity of space.

Following [2], the clocks from the rest system, $S$, can be synchronized using Einstein's procedure with light signals, since the one-way speed of light is $c$ in this frame[2]. In any

[2] Alternatively, the slow clock transport would be possible as well. This method will be discussed in detail elsewhere.

moving inertial frame, the common time can be established with the help of the clocks at rest. In particular, the moving clocks can be synchronized simply by adjusting them to zero whenever they fly past a clock at rest that shows zero as well [2]. From that moment on, the moving clocks remain synchronous between themselves, thus establishing the common time of the moving system. Clocks synchronized in this way are denominated by *synchronized clocks*. Of course this is not the synchronization procedure adopted by Einstein. Nevertheless, it is a possible and simple one. And, let us insist, physics and its laws are not changed by the way the clocks have been set.

From the constancy of the two-way speed of light and the synchronization method above, the relations between space and time coordinates providing the translation from the description of a certain event in the rest system $S$ to the one in a frame $S'$ moving along the $x$-axis are given by [2]

$$x' = \gamma(x - vt), \qquad t' = \frac{t}{\gamma}, \tag{1}$$

where $\gamma$ is given by

$$\gamma = \frac{1}{\sqrt{1 - \frac{v^2}{c^2}}}, \tag{2}$$

and $v$ is the absolute speed of the moving frame, i.e., its speed in $S$. Expressions (1) form the *IST transformation* (inertial-synchronized-Tangherlini). We have denoted it previously by synchronized transformation. However, they have been emphasized by Franco Selleri since 1996 [6–8], who named them inertial transformations, and were obtained by Tangherlini in 1961 [9]. Expressions (1) were also given and discussed in the beautiful work of Mansouri and Sexl [10].

If an object travels with (absolute) speed $w$, then its relative speed, $w_v$, in relation to a frame $S'$ moving with (absolute) speed $v$, is given by

$$w_v = \gamma^2(w - v) = \frac{w - v}{1 - v^2/c^2}. \tag{3}$$

In particular, the one-way speeds of light along $x$ in $S'$ are given by

$$c_v^+ = \gamma^2(c - v) \tag{4}$$

and

$$c_v^- = \gamma^2(c + v). \tag{5}$$

Besides non-invariant one-way speed of light, the IST transformation exhibits absolute time dilation, absolute space contraction and absolute simultaneity. How these statements can be compatible with Einstein's special relativity was studied by many authors, e.g. [6, 10–13], and reviewed in [2]. Basically, the Lorentz transformation can be obtained from the IST transformation by delaying the moving clocks by a factor proportional to their distance $x'$ to the reference position $x' = 0$, which is given by $(v/c^2)x'$. The clocks altered in this way are designated by *Lorentzian clocks*, and their time readings, $t'_L$, by *Lorentzian times*:

$$t'_L = t' - \frac{v}{c^2}x'. \tag{6}$$

Substituting (6) in (1), one gets the Lorentz transformation. That being so, *any event or set of events that can be described by the Lorentz transformation can be described as well by the IST transformation*: they only differ by a change of *coordinates*, so that both descriptions are *mathematically equivalent*. This should not be too surprising after all, since we can set clocks in different ways, but we are describing *one and the same reality*, which is independent of the coordinates chosen [12]. We can even use both types of clocks at the same time! [2].

As anticipated in [2], the interest in de-synchronizing clocks according to (6) is related to the problem of performing an *internal* 'synchronization' of the moving clocks, discussed during this paper. We shall use the word 'synchronization' to denote the external synchronization leading to the IST transformation, other 'synchronization' procedures being always explicitly identified.

Finally, the *Einstein speed*, $v_E$, is defined as the 'speed' measured with Lorentzian clocks (and ordinary rulers) [2],

$$v_E = \frac{\Delta x}{\Delta t_L}, \tag{7}$$

where the time interval is calculated as the difference of the 'time reading of a Lorentzian clock located at arrival position' with the 'time reading of a Lorentzian clock located at departure position'. The 'Einstein speed' $v_E$, measured in a frame moving with absolute speed $v$, of an object which has absolute speed $w$, is

$$v_E = \frac{w_v}{1 - v w_v/c^2} = \frac{w - v}{1 - v w/c^2}, \tag{8}$$

and, consequently, *the 'Einstein speed' of light is always c in any moving inertial frame, independently of the speed of the moving frame* [2].

## 3. From Galileo to Einstein

After the brief review of previous work and definitions presented in section 2, we can now turn our attention to the principle of relativity.

The origins of the principle of relativity are usually attributed to Galileo and to his 1632 'Dialogue Concerning the Two Chief World Systems' [14], although, as pointed out by Martins [15], very similar arguments have been previously used by Nicole Oresme in 1377, Giordano Bruno in 1584 and by Galileo himself in 1624 (in a letter to priest Francesco Ignoli). Anyway, in the defence of the heliocentric system, Galileo argued that it is not possible to conduct a physical experiment capable of indicating if a body is immobile or in motion. He used in the 'Dialogue' a famous metaphor with a ship, Sagredo concludes

> I am therefore satisfied that no experiment that can be done in a closed cabin can determine the speed or direction of motion of a ship in steady motion.

Galileo mentioned the need to be 'below decks' (not quoted here) and 'in a closed cabin'. He used this example in order to show that one cannot determine whether the earth is revolving or fixed, in the same way that from the motion of butterflies one cannot determine if a ship is moving or standing still. It is often considered he wanted to stress the idea that there is no meaning in the concept of a moving body without reference to its movement *relative* to another body. This is *not* true: if it would be only a question of relative movement, there would make no difference to consider either the earth moving or the sun moving. Galileo was convinced that saying the earth revolves and the sun is immobile is closer to reality than the reverse, but in fact he could *not* find a strong and unquestionable argument to support his view. Hence, his purpose was 'only' to show that the everyday experience was not in contradiction *either* with an earth moving *or* with an immobile earth. He argued that it is difficult to decide if it is the earth or the sun that is at (absolute) rest, because we can only perceive relative motion. That the effects observed in experiments performed on earth are the same regardless of what motion the earth really has, being thus impossible, by experiments performed on earth, to solve the doubt. Galileo was actually going after the idea of *absolute* motion and *absolute* rest. Even though, it is sometimes stated that the work of Galileo has shown that the notions of 'rest' and 'movement' are strictly *relative*, velocity having meaning *only* as 'relative velocity'. This is manifestly incorrect. Galileo has shown the importance of relative motion, yes, but there is no inconsistency between the notion of absolute rest and Galileo's work. Quite on the contrary.

Galileo's *principle of relativity* is summarized in the quote above: with an experiment conducted inside a closed cabin, it is not possible to decide if the ship is at rest or in steady motion. But there is an important observation, which is the mentioned comment about the need to be below decks, as discussed below.

The principle of relativity was first enunciated by Newton in 1729 [16], in the line of Galileo's example:

> the motions of bodies included in a given space are the same among themselves, whether that space is at rest, or moves uniformly forwards in a right line without any circular motion.

Contrary to Galileo, who argued that any 'common motion is as non-existing' (and this included Earth's rotation), Newton makes the important restriction of considering only uniform motion along straight lines, i.e., inertial frames. To Newton there existed one absolute space and a multitude of inertial systems. Even if empirical observations cannot detect if a certain body is at absolute rest, Newton felt the need of introducing the former in order to define the latter. Moreover, he needed the concepts of absolute space and absolute rest to state the first law of motion: that every body continues in its state of rest, or of uniform motion in a 'right' line, unless it is compelled to change that state by forces impressed upon it. To Newton, without the assumption of absolute space no meaning could be given to the notion of rest, which seemed to him it could not be dispensed within the formulation of the first law.

Historically, it is of major importance that the laws of classical mechanics look identical in all moving inertial frames and in the rest system when Galileo transformation of coordinates is used. Poincaré [17] and Einstein [18] generalized this idea to *all* laws of physics. Poincaré includes the principle of relativity among the 'five or six general principles to the various physical phenomena',

> The laws of physical phenomena must be the same for a 'fixed' observer as for an observer who has a uniform motion of translation relative to him, so that we have not, and cannot possibly have, any means of discerning whether we are, or are not, carried along by such a motion.

Very remarkably, Poincaré's principle of relativity is formulated under the assumption of absolute space. To Poincaré, that one cannot have means to detect absolute motion is not contradictory with its existence. All frames *appear* to be equivalent, even if they are not. Feynman called it a *nature conspiracy* [4]: since many experiments devised to measure an absolute speed $u$ seem to have failed,

> it appeared nature was in a 'conspiracy' to thwart man by introducing some new phenomenon to undo every phenomenon that he thought would permit a measurement of $u$. It was ultimately recognized, as Poincaré pointed out, that *a complete conspiracy is itself a law of nature!* Poincaré then proposed that there *is* such law of nature ( . . . ); that is, there is no way to determine an absolute speed.

Soon after Poincaré, Einstein formulates the principle of relativity in the form

> not only the phenomena of mechanics but also those of electrodynamics have no properties that correspond to the concept of absolute rest. Rather, the same laws

of electrodynamics and optics will be valid for all coordinate systems in which the equations of mechanics hold.

After Galileo's epic struggle in favour of the heliocentric system and 100 years of Einstein's celebrated theory of relativity, which contributed decisively to the progressive abandon of the notion of absolute space in favour of that of 'equivalence' between all inertial frames, many textbooks on elementary physics state the principle of relativity by stressing that the laws of physics 'must be the same' in all inertial reference frames, or even stating directly that all inertial frames are 'equivalent'. Both statements are rather subtle. For instance, Poincaré assumed the existence of absolute motion, so what does 'equivalent' mean? Moreover, there is a crucial difference, usually unremarked in textbooks, in affirming 'the laws of physics are the same' or 'the laws of physics keep the same form' (section 4.3). And keep the same form under which circumstances? How fundamental is this 'invariance'?

In its genesis the relativity principle is a 'principle of relative movement', hence its name. It is solely related to the impossibility of detecting absolute motion. In order to keep it completely clear, we suggest to recover this idea of a 'principle of relative motion', in the line of what is done in 'Feynman lectures on physics' [4], a noticeable exception among physics textbooks, and to leave further considerations to a subsequent step. As a matter of fact, Feynman puts it luminously, with an important and barely seen observation, noted here in italics:

> if a space ship is drifting along at a uniform speed, all experiments performed in the space ship will appear the same as if the ship were not moving, *provided, of course, that one does not look outside*. This is the meaning of the principle of relativity.

That one cannot look outside is the equivalent of Galileo's remark about being in a closed cabin. Here, we take the principle of relativity as enunciated by Feynman, with the additional constraint of being in vacuum (discussed in detail in [5, 19]):

- All the experiments performed in a closed cabin in vacuum in any moving inertial frame will appear the same as if performed in the rest system, provided, of course, that one does not look outside.

Note that the interdiction of looking outside raises an extremely delicate point for the Lorentz–Poincaré view. In fact, in the very construction of a moving inertial frame, as presented in section 2, we *have to look outside* in order to synchronize the moving clocks by comparison with the clocks of the rest system. In this sense, the procedure of synchronization is an *external* one. This fact casts a new light into the meaning of the principle of relativity that we develop in the remaining sections of this paper.

For the moment, let us still note that [4]

> Our inability to detect absolute motion is a result of *experiment* and not a result of plain thought ( . . . ). There is a philosophy which says that one cannot detect *any* motion except by looking outside. It is simply not true in physics. True, one cannot perceive a *uniform* motion in a *straight line*, but if the whole room were *rotating* we would certainly know it ( . . . ). It is only *uniform velocity* that cannot be detected without looking outside. Uniform *rotation* about a fixed axis *can* be.

Evidently, this is known by any physics student. The interesting idea Feynman emphasizes is the following: if we look outside, we can easily verify if we are rotating or not, by seeing the changes in our position in relation to the outside 'static' world. Furthermore, if we do *not* look outside, we can *also* determine if we are rotating, just by means of an internal experiment.

*Both* observations are concordant. *A priori*, the same reasoning could in principle be applied to uniform motion, although observation is a bit more difficult. However, the principle of relativity (in vacuum) asserts that if we do not look outside, then we cannot say whether we are moving or not, i.e., the internal observation is not consistent with the external one. This is what happened with the Michelson–Morley experiment, which was precisely an attempt to obtain the speed of the earth without looking outside. Note that the value of the speed of the earth was already known using procedures that involved looking outside. But the internal measurements seem to have failed to provide a consistent observation. In [1], it was suggested this had to be so in vacuum. The question of propagation of light in rarefied gases was discussed in [19] and is briefly referred to at the end of this paper.

## 4. Special relativity

In this section, we show how the Lorentz transformation comes forth from the principle of relativity enunciated in the previous section and from the weak formulation of the postulate of the constancy of the speed of light made in section 2. Nonetheless, it is emphasized that, despite its specific role, the Lorentz transformation is just a transformation of *coordinates* and that many other coordinate transformations can be used as well. Moreover, it has drawn attention to the fact that the laws of physics are the same for all inertial observers, whether or not they keep the same form under a particular transformation of coordinates.

### *4.1. Internal 'synchronization'*

As we have just seen, the principle of relativity raises the question of what can be done to somehow 'synchronize' moving clocks without looking outside, i.e., to perform some *internal* 'synchronization'. The word 'synchronization' must be used with care. Plain and simple, what is necessary is to find a way to give some well defined starting condition for all the clocks in a particular inertial frame. These conditions can then be *defined* as clock 'synchronization' (although they may not correspond to the everyday notion of a true synchronization). There is no problem at all in doing so. For instance, synchronized and Lorentzian clocks are set in different ways; nevertheless, *both* are good enough to make time measurements and *both* can be used to study physics. As long as we know, of course, what kind of clock is being used. In [2], even a third type of clock—a Galilean clock—was used.

In the rest system $S$ as defined in section 2, there is no need to look outside. Since the one-way speed of light is known to be $c$ in every direction, the synchronization procedure of the clocks at rest is in fact an internal one. It is worthwhile to reiterate that, at this point, there is still no element of convention involved. Furthermore, for the discussion of this principle, at the present stage it is irrelevant if the rest system can be experimentally identified internally or not, as mentioned in section 2 and in [2].

Now, suppose an inertial frame $S'$ is moving with absolute speed $v$ along $x$. If the observers in $S'$ cannot look outside, they do not know they are moving. How can they 'synchronize' internally their clocks? Without a better choice, they can just carry on *as if* they were at rest. They can simply assume the one-way light 'speed' to be $c$ in every direction in their own frame—although maybe it is not—and then make the internal 'synchronization' of their clocks consistent with this assumption. In fact, they have no idea if the one-way speed of light *is indeed* $c$ (see sections 5 and 7 for very short comments on the conventionality thesis).

As mentioned in section 2 and discussed in [2], it is beyond doubt that different types of clocks simply provide different time *coordinates* to describe the *same reality*. In addition, the words 'time', 'speed' and 'simultaneity', which we use to attribute a precise physical meaning, actually refer to *different* notions when different types of clocks are used. Since different descriptions, made with various types of clocks and rulers, are mathematically equivalent, this latter issue is mainly a question of language. Nonetheless it is an important one and likely to originate severe misunderstandings, because the physical concepts underlying each of these descriptions are quite different. Many disputes and hot debates around special relativity are related to this problem of using the same *word* to designate different *concepts*. For these reasons, it is of major importance to know with what kind of clocks one ends up after performing an internal 'synchronization'.

It is not too difficult to realize that *internally 'synchronized' clocks are Lorentzian clocks*. In section 2, 'speeds' measured with Lorentzian clocks were designated by Einstein speeds. It has been subsequently seen that the one-way Einstein speed of light is $c$ in all inertial frames. As a consequence, when the internal 'synchronization' is done and the one-way 'speed' of light is imposed to be $c$, Einstein speeds and Lorentzian clocks are in fact being used. There is no problem with it, as long as we are aware we are doing so. Moreover, it is very simple to proceed in this way (although not mandatory), in particular if it is not possible to look outside or to identify the rest system.

It is worth noting that the possible *slow transport method* of clock 'synchronization' mentioned in section 2, consisting of setting the clocks at the same location and then to move them slowly until they reach their final positions, is equivalent to the internal 'synchronization' scheme. Hence, it can be used to synchronize clocks in the rest system, but leads to (de-synchronized) Lorentzian clocks if used in a moving inertial frame. The detailed calculations are not of major interest here, and can be found, for instance, in the 2003 works of Homem [20] and Szabó [21] or in the much earlier book by Eddington [22].

There is an easy analogy between the internal 'synchronization' of clocks using light speed *as if* it was $c$ in all directions and 'synchronization' of clocks around a race track using a $F_1$ car *as if* its speed was constant. Suppose a $F_1$ car is going in a circuit, doing a few laps exactly in the same way. Someone is standing with a clock at the start/finish line, and registers the time the $F_1$ takes to make one lap. Knowing the length of the track, it is easy to find the average speed of the $F_1$ during the lap. This time measurement is of course made with only one clock, located at the start/finish line. In respect to the light 'synchronization' of clocks, this first measurement is equivalent to verifying that the two-way speed of light—the average speed of light in a round trip—is actually $c$. Next, imagine that several other observers are sitting in some other spots of the circuit. At a certain arranged lap, the person at the start/finish line sets his clock to mark zero when the $F_1$ crosses the line. Then, each of the other observers sets his own clock to mark the 'distance of his location to the start/finish line' over 'average speed of the $F_1$' when the car passes. This corresponds to 'synchronizing' the clocks *as if* the $F_1$ speed was constant and equal to its average speed all the way around the circuit, even if it is not. In the end all observers have their clocks 'internally synchronized with the speed of the $F_1$'. Obviously the real speed of the $F_1$ is not its average speed in all parts of the circuit. But from now on, a 'speed' measurement made with these clocks will always give this value. Because the clocks have been set using such a procedure that it cannot be otherwise. The same situation occurs with the internal 'synchronization' of clocks with the speed of light. All observers in a moving frame can 'synchronize' their clocks with light signals *as if* the one-way speed of light was constant and equal to $c$ in all directions (even if it may not be). In the end they will have their clocks internally 'synchronized'. And from now on, the one-way 'speed' of light measured with these clocks—the Einstein speed of light—will always be $c$. Because the clocks have been set using such a procedure that it cannot be otherwise.

### *4.2. The role of the Lorentz transformation*

We are now ready to have a close look at Einstein's theory of special relativity. This theory is built from two postulates, the principle of relativity and the constancy of the speed of light. In his 1905 article [18], Einstein starts with the definitions of simultaneity, synchronization and time for the 'rest system'. Subsequently, he verifies what happens when two moving observers, each carrying his own clock, 'apply to the two clocks the [same] criterion for the synchronous rate of two clocks'.

In this way, in Einstein's theory of relativity, the observers in moving inertial frames proceed *as if* they were at rest. In particular, and in order to 'synchronize' their clocks, all inertial observers assume the one-way speed of light in empty space to be $c$, independently of the state of motion of the emitting body. Einstein's synchronization of clocks is thus the internal 'synchronization' detailed above, corresponding to the use of Lorentzian clocks. That being so, speeds are the 'speeds' measured with Lorentzian clocks (i.e., precisely what we have defined as Einstein speeds), and the associated transformation of coordinates between inertial frames is the Lorentz transformation.

All Einstein's definitions are extremely precise, clear and full of physical content. However, as discussed in detail in [5] and outlined in [2], the words 'synchronization', 'simultaneity', 'time lapse' and 'speed'—which depend on a particular choice of *coordinates* [12]—must be used with caution. Because in a sense they become false friends and more than often originate misinterpretations. They were redefined in such a way as to make the study of physical phenomena most simple and elegant, but have lost to some extent their intuitive meaning. For instance, no one really understands instinctively how can it be that 'the one-way speed of light in vacuum is $c$ in all inertial frames, independently of the speed of the source'. All students pass through this shock, and essentially they simply get used to the idea after a while, by learning how to perform the calculations. In his exceptional book [23], David Morin does not hide this problem, underlining it as follows:

> I do not claim that this statement is obvious, or even believable. But I do claim it's easy to understand what the statement says (even if you think it's too silly to be true).

On the other hand, the sentence 'the one-way Einstein speed of light is $c$ is all inertial frames' is a complete triviality.

In the standard interpretation of special relativity, *all inertial frames are 'equivalent'*. No inertial reference frame is better than any other. It is commonly stated that this equivalence of all inertial frames means that the laws of physics *are the same* in all inertial frames. This is actually how the principle of relativity is presented in many textbooks. However, as is shown below and further emphasized in section 4.3, this statement, as is, is not only misleading but meaningless. Anyway, under the standard interpretation of special relativity widely divulged, the impossibility of detecting absolute motion internally is seen as a *consequence* of this postulated equivalence of all inertial frames. In this sense, *the equivalence of all inertial frames is more fundamental than the impossibility of detecting absolute motion*, although the latter is widely recognized as the motivation for stating the former.

Herein we suggest the recovery of a weaker formulation of the principle of relativity, complying with experimental evidence and free of unnecessary additional assumptions. In section 3, we have enunciated it as

- All the experiments performed in a closed cabin in vacuum in any moving inertial frame will appear the same as if performed in the rest system, provided, of course, that one does not look outside.

We stressed the importance of not looking outside. As a matter of fact, *if* one does not look outside, then the 'synchronization' of clocks must be done internally, leading to Lorentzian clocks. Therefore, all moving inertial frames, when equipped with Lorentzian clocks, appear to be equivalent: all experiments and measurements made with Lorentzian clocks in a moving frame must give the same result as if they were made in the rest system. Our principle of relativity can hence be rewritten in the following way:

- All laws of physics, when written with Lorentzian coordinates—i.e., with Lorentzian times and Einstein speeds—keep the same form in all inertial frames, the same as in the rest system.

This is the meaning of the Poincaré 'nature conspiracy'. With Lorentzian coordinates, any moving inertial frame appears to be the rest system. In this way, *the impossibility of detecting absolute motion without looking outside is more fundamental than the supposed equivalence of all inertial frames*, as emphasized by authors like Fock [24].

It should be mentioned that Feynman [4] makes a not so traditional presentation of Einstein's special relativity and writes the principle of relativity correctly. As noted before, he is among the very few to have stressed the importance of not looking outside. Moreover, and strikingly as well, he discusses the 'invariance' of the laws of physics in the correct way: '*all the physical laws* should be of such a kind that they *remain unchanged under a Lorentz transformation*'.

Contrary to most textbooks, Feynman does not simply state that the laws of physics keep the same form (or are the same) in all inertial frames, but specifically mentions the crucial role of the Lorentz transformation.

The Lorentz transformation has almost a magic aura in physics due to its mathematical properties of invariance of the laws of physics. They are strongly connected with the fact that the Lorentz transformation is the natural transformation of coordinates that arises when a moving inertial frame is treated *as if* it was the rest system, because we do not want or cannot look outside. Due to their symmetry, Lorentzian coordinates are practical and extremely useful in the study of physics. Nevertheless, other coordinates can evidently be used: the laws of physics exist *independently* of the coordinates used to describe them. And *are the same* whatever coordinate transformation is used, even if they do *not* keep the same form. Poincaré has noted it beautifully in 1898 [25], discussing Newton's second law and the adoption of an unusual way of measuring time. He wrote that

> the experiments on which Newton's second law is founded would nonetheless have the same meaning. Only the enunciation of the law would be different, because it would be translated into another language.

The following subsection reinforces this idea.

### *4.3. A word on geometric objects*

The group property of the Lorentz transformation is used frequently, but erroneously, as an argument to rule out the Lorentz–Poincaré philosophy. Let us recover Feynman's introduction to vectors [4]. This is too elementary, but the mistake of claiming that the Lorentz transformation *implies* that the so-called aether frame does not exist is so common that we find it worthwhile to repeat it here. Feynman introduces vectors in the following way:

> A vector is three numbers. In order to represent a step in space, say from the origin to some particular point P whose location is $(x, y, z)$, we really need three numbers, but we are going to invent a single mathematical symbol, $\mathbf{r}$ (...). It is *not* a single

> number, it represents *three* numbers: $x$, $y$ and $z$. It means three numbers, but not really only *those* three numbers, because if we were to use a different coordinate system, the three numbers would be changed to $x'$, $y'$ and $z'$. However, we want to keep our mathematics simple and so we are going to use the *same mark* to represent the three numbers $(x, y, z)$ and the three numbers $(x', y', z')$. ( . . . ) This has the advantage that when we change the coordinate system, we do not have to change the letters of our equations. ( . . . ) The three numbers which describe the quantity in a given coordinate system are called the *components* of the vector in the direction of the coordinate axes of that system. That is, we use the same symbol for the three letters that correspond to the *same object, as seen from different axes*. The very fact that we can say 'the same object' implies a physical intuition about the reality of a step in space, that is independent of the components in terms of which we measure it. ( . . . ) An equation like
>
> $$\mathbf{F} = \mathbf{r}$$
>
> would thus be true in *any* coordinate system if it were true in one.

In this sense, the *physical laws* are geometric objects themselves, they are valid in any coordinate system if they are valid in one. It does not matter what *form* the *components* take in one particular coordinate system: it is always the same law. Note that besides the quantities depending on the coordinates chosen, others are coordinate-independent, and are thus *intrinsic* features of the vector. An example of the latter is the 'length' or norm of the vector.

Rather surprisingly, these simple notions seem still far from obvious when generalized to special relativity. One of the beautiful discoveries of special relativity was that of the *metric properties of spacetime*, in what is known as the Minkowski spacetime and the associated 4-vectors. Of course, a 4-vector is four numbers, $X = (ct, x, y, z)$, with one *time component*, $ct$, and three *space components*. This vector is an object that represents reality independently of the components in terms of which it is written. And it has a certain norm, which is independent of the system of coordinates chosen.

Leubner and co-workers have published a very clear article about this problem in 1992 [12]. It is unfortunate that their work is not better known. Their point is the following:

> the fact that different synchronization conventions imply different coordinatizations of spacetime with ensuing changes of the form of possibly all coordinate-dependent quantities, has neither entered textbooks nor undergraduate physics education. As a consequence, there is a widespread belief among students that the familiar form of coordinate-dependent quantities like the measured velocity of light, the Lorentz transformation between two observers, 'addition of velocities', 'time dilation', 'length contraction', '$E = mc^2\gamma$', which they assume under the standard clock synchronization, is relatively proper. This is by no means so. ( . . . ) The message clearly conveyed is that in the teaching of elementary relativity much more stress should be laid on the intrinsic (coordinate-independent) features of spacetime.

As an exercise, Leubner *et al* adopt a non-standard clock synchronization that they name 'everyday' clock synchronization (which corresponds to the IST transformation (1) with $v = -c$ and is similar to the one presented by Edwards [11]), and note that

> phrases like 'moving clocks go slow', 'moving rods are shortened' and 'simultaneity is relative' are no longer true under the adopted non-standard clock synchronization and, hence, are by no means intrinsic features of Minkowski spacetime.

The idea is simple and straightforward. The Lorentz transformation and the ‘invariance’ of the form of the laws of physics when written with Lorentzian coordinates are connected to the principle of relativity and doing physics by not ‘looking outside’, but we can make *all* physics with the coordinates that please us the most. It is precisely the same physics. And once it is understood that the different transformations of coordinates correspond only to a change in the way of writing the *components* of a 4-vector or tensor, but not of the 4-vector or tensor itself, the mistake of identifying the principle of relativity with the pointless assertion ‘the laws of physics are the same in all inertial frames’ is no longer made. In this line, a coordinate-free approach to electrodynamics was developed by Ivezić in [13] and by Oziewicz in [26]. Furthermore, it follows that the IST, which refers to an absolute rest system, is valid if the Lorentz transformation, with no reference to it, is. What is still missing is then to debate how the symmetry of the Lorentz transformation is inferred and understood within a structure that is close to the Lorentzian philosophy. This is done in the following section.

## 5. The indeterminacy of special relativity

The standard interpretation of special relativity, with its equivalence of all inertial frames, is the theory of the ‘points of view’. The real situations—and ultimately reality—do not look like one thing in particular. As put by Morin [23],

> there is no such thing as ‘is-ness’, since the look depends on the frame in which the looking is being done.

Of course things depend from the frame in which the looking is being done. As noted once more by Feynman [4], ‘a person looks different from the front than from the back’. But Morin’s ‘is-ness’ refers to much more unusual and relevant things. Within the standard interpretation of special relativity, it is accepted it makes no sense to say things such as ‘two events are simultaneous’, ‘clock A runs slower than clock B’ or ‘train A is longer than train B’. The answer to these questions depends upon one’s point of view.

However, everything that can be described by the Lorentz transformation, with its lack of ‘is-ness’ of reality, can as well be described by the IST transformation, with its absolute assertions about simultaneity, clock rhythms and length measurements. *As long as the absolute speeds of the moving frames are known*, it is immediate to make the transformation of coordinates, and translate Lorentzian times and Einstein speeds into synchronized times and absolute speeds. But if these absolute speeds are unknown, then it is impossible to transform the Einstein speeds resulting from an internal synchronization into absolute speeds. In this sense, although both descriptions are mathematically equivalent, the Lorentz transformation *contains less information* than the IST transformation. Now, if Poincaré’s nature conspiracy holds, then it is hopeless to experimentally determine the one-way speed of light. And *without the measurement of the one-way speed of light relativity theories remain undetermined and incomplete*. All it can be done is to proceed ‘as if’.

To our knowledge, with his idea of a nature conspiracy, Poincaré was the first to somehow touch the problem of the indeterminacy of special relativity [17]. Referring to a method of clock synchronization with light similar to Einstein’s one, Poincaré noted that two clocks in stations A and B

> indeed mark the same hour at the same physical instant, but under one condition, namely, that the two stations are stationary. Otherwise, the time of transmission will not be the same in the two directions. ( . . . ) Watches regulated in this way, therefore, will not mark the true time; they will mark what might be called the local time, so

> that one will gain on the other. It matters little, since we have no means of perceiving it. All the phenomena which take place at A, for example, will be behind time, but all just the same amount, and the observer will not notice it since his watch is also behind time; thus, in accordance with the principle of relativity he will have no means of ascertaining whether he is at rest or in absolute motion.

Note that the notions of 'true time' and 'local time' were also used by Lorentz [27] in an outstanding article whose contents deserve to be better known. The indeterminacy of relativity theories may look rather disappointing, but it is not too big a problem to live with. What is important is to know exactly what we are doing and what we are measuring.

It is at this point, and at this point only, that a deadlock arises in practical terms—though not in fundamental ones—and additional assumptions are required. It is only at this stage that philosophical or interpretation issues may be invoked and may take the subsequent development of the theory into diverse paths.

One possibility to solve the impasse is to accept the indeterminacy by understanding that the knowledge of the true value of the one-way speed of light is somewhat 'superfluous'. As a matter of fact, relative motion can be studied without any mention to absolute motion. As an *operational procedure*, we can treat *all* moving inertial frames *as if* each of them was the rest frame. In this case, all moving frames become furnished with Lorentzian clocks and thus measure Einstein speeds. Similarly to the $F_1$ car synchronization example, in which it is impossible to infer the real speed of the $F_1$ car in any part of the circuit from a 'speed' measurement, without the knowledge of which is the rest system (or of the real value of the one-way speed of light) it is not possible to know the real (absolute) speeds and time intervals from the 'speeds' and 'time intervals' actually measured with Lorentzian clocks. In this view, there is only one theory, Bell's two philosophies corresponding just to different aspects of the same theory. This is the view defended by Duffy [28] that we subscribe to a big extent.

Another possibility is to give a further step and consider any mention to absolute motion as completely *irrelevant* to physics. This comes associated with a strong *operationalist* view, where only observable quantities are thought to be of relevance to physics. This idea may evolve in two ways. One is within the conventionality thesis, where it is said that the value of the one-way speed of light is just a matter of convention. Sometimes it is even stated that we can only speak about quantities that we can measure, and so there is nothing in the physical world corresponding to the concept of a one-way speed! We strongly oppose this view and find that the only possible convention is the choice of which *word* is used to denote which *concept*. Different concepts coexist and their meaning is not changed by the names we choose to denote them. This issue was also illustrated in [2] and further remarks on the conventionality thesis and operationalism are made in section 7. The second possible development is with the notion or assumption that the real value of the one-way speed of light is indeed $c$ for all moving observers, independently of the speed of the source. However, this brings 'paradoxes' and interpretation difficulties, unless we keep in mind the word 'speed' was redefined, or else if we accept we have to reason in more abstract terms, losing contact with a tangible reality.

Finally, many students and scientists still consider any mention of absolute motion as *erroneous*. This statement can be done solely on philosophical grounds, by adopting a minimalist point of view. It is not implied by the theory, as there is nothing contradictory between Einstein's special relativity and the assumption of a preferred reference frame. Actually, it is the assertion which is incorrect and, as such, should not be accepted in physics.

Evidently, one can use the indeterminacy of relativity theories to adopt any view he wishes, as long as no inaccurate statements are made. We may use the language as we want and *define* a meaning for the names 'synchronization', 'simultaneity' and 'speed' in many

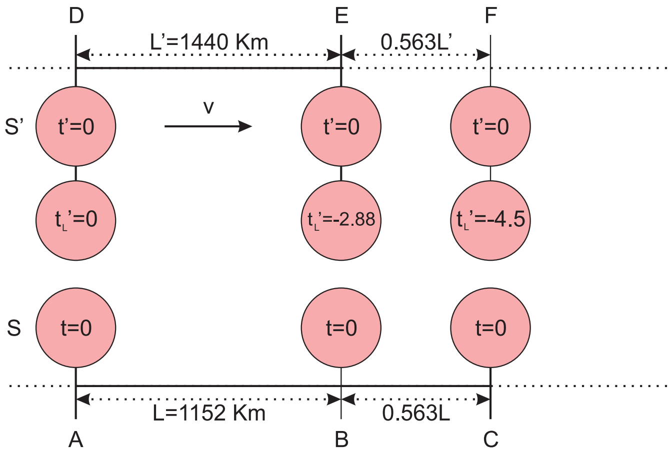


**Figure 1.** Space contraction both with synchronized and Lorentzian clocks. All times in the figures are expressed in ms. Initial situation is at $t = 0$.

different ways. Reality *is* independent of the names we use to describe it. In the end what really matters is that one makes sure that none of these words is used in some context and interpreted in a different one.

## 6. Absolute and relative length contraction

This section treats the classical problem of length contraction using a very simple example, to illustrate the claim that the relativity of length contraction 'deduced' from the Lorentz transformation is fully compatible with the absolute length contraction obtained from the IST transformation. We present the example within the context of the weak formulation of the postulates proposed here, *before* making any of the additional assumptions that can be made to solve the indeterminacy of special relativity.

The rest system defined in section 2 is used in the example. Certainly we can invoke that we cannot experimentally determine it, but this does not invalidate the example, which can be seen as a thought experiment.

Consider the initial setup depicted in figure 1. There are two rigid rods, one between clocks A and C, identifying the rest system $S$, and the other connecting clocks D and E, defining a moving frame $S'$ going with speed $v = 0.6c$ (so that $\gamma = 1.25$). The rods have several clocks attached to them. The moving rod in $S'$ is equipped *both* with synchronized and Lorentzian clocks. We will use both types of clocks to analyse this particular configuration. Both rods have a mark at each kilometre, labelled from zero (at the positions of clocks A and D) to their total lengths (at the positions of clocks C and E). Observers in each frame can look to the other frame and check which are the marks on both rods that are just in front of them. Evidently, the marks in the rigid rods in both frames are exact copies of each other. This means that when the rods of both frames are brought together, their 'meters' have the same size. The same is true for the clocks in both frames. When they are brought together, they have the same rhythm.

From figure 1, the observers at rest say the extremities of the moving rod are aligned with clocks A and B. The length of the moving rod is thus the distance $\overline{\mathrm{AB}}$, $L = 1152$ km. They also see the marks on the moving rod, verifying its length in $S'$ to be $L' = 1440$ km. This means

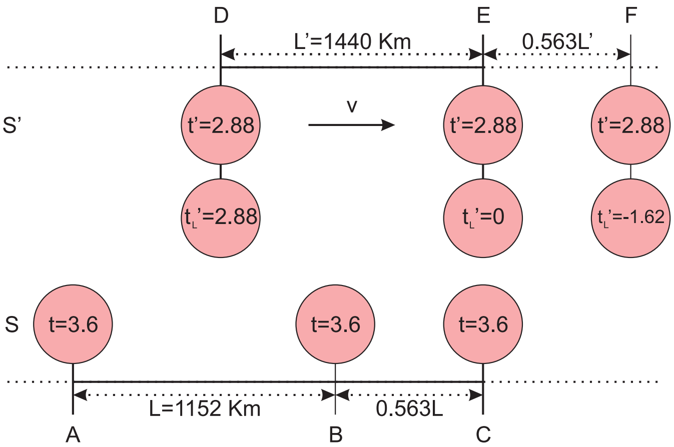


**Figure 2.** Evolution from figure 1 is shown here at $t = 3.6$ ms.

that space is contracted in the moving frame $S'$; in this case, by a factor of $1440/1152 = 1.25$. Since the moving 'meters' have become shorter, the moving observers measure a bigger length for the distance $\overline{\mathrm{AB}}$, corresponding to the length of their rod. These affirmations have nothing to do with the initial adjustment that is made to the moving clocks, i.e., on the type of clocks that is being used.

Let us now see how the observers from $S'$ describe the same situation. Well, if they use their synchronized clocks (or if they use their Lorentzian clocks and they know the speed of $S'$ in order to translate the Lorentzian coordinates into synchronized ones), they simply say the same as the observers from $S$: the length of the moving rod is $L = 1152$ km in $S$ and $L' = 1440$ in $S'$. There is nothing more to be noted.

Clearly, there is *no* reciprocity between frames: the rod from the rest system $S$ is truly at rest, even if it can be seen as moving in relation to $S'$, and has thus a shorter length.

However, if the observers in $S'$ do not know they are moving, they can use their Lorentzian clocks and proceed *as if* they were at rest. Of course this affects the measurements of distances, since the 'length' is measured by determining at which points the beginning and the end of the rod to be measured are located 'at some instant', i.e., both positions have to be measured 'simultaneously'. The situation corresponds then to the typical problem studied in introductory special relativity: one of the extremities of the rod in $S$ is measured by observer D in the conditions of figure 1, while the other is measured by observer $E$ at a later time, in the situation shown in figure 2. There is no need to take the example exhaustively to the end and the reader is invited to check it out without equations and simply with the help of figures 1 and 2. As is well known, the rod from $S$ would appear to be contracted seen from $S'$ by a factor 1.25, as it had to be. However, this effect has nothing to do with lengths of rods and it is merely a result of taking the space coordinates 'simultaneously' using (de-synchronized) Lorentzian clocks.

The relativity of space contraction is just a mathematical result coming from the utilization of Lorentzian clocks to write down the coordinates of an object, *not observable with clocks adjusted in a different way*. This example illustrates as well the correct formulation of the principle of relativity: when Lorentzian coordinates are used, all inertial frames appear to be equivalent, so that 'the observers from $S'$ see $S$ in the same way as the observers from $S$ see $S'$'. Accordingly, the *description* of space contraction that is made with Lorentzian clocks is indeed symmetrical between $S$ and $S'$. But reality does not change by the way the clocks have been set.

Similarly, and as pointed out in a related example shown in [2], the *rhythms* of both synchronized and Lorentzian clocks *are precisely the same*. For *each* of the clocks in $S'$, synchronized or Lorentzian, 2.88 ms have passed from the situation in figure 1 to the one in figure 2, while for each of the clocks in $S$ 3.6 ms have passed. Time dilation is also absolute if referring to the rhythms of the clocks. However, it is seen as a relative phenomenon if it refers instead to a comparison of the Lorentzian *coordinates* exhibited by the clocks.

## 7. Discussion and conclusion

It is our firm belief that physics should assume itself as the heir of *natural philosophy*. And thus question, with no fear nor prejudice, the postulates or hypothesis at the origin of each theory. Only in this way is it possible to claim that to understand a physical theory goes much beyond the simple knowledge of how to perform the calculations. Unfortunately, special relativity is presented in most textbooks by passing too swiftly over the discussion of its postulates. This work ends a trilogy devoted precisely to a longer visit into the foundations of special relativity. In this series, we also sketch how we conceive the teaching of the theory.

John Bell suggested that special relativity should be taught using a Lorentzian pedagogy first [3]. He claims such an approach develops the intuition of students and prevents them from making basic mistakes. He has even noted that most of his colleagues at CERN started by giving the wrong answer to a simple relativity problem, only giving the right answer on further reflection. Leubner *et al* made a related proposal, advising that the emphasis in teaching relativity should be put on the intrinsic (coordinate independent) features of spacetime since the beginning [12]. They suggest relativity to be studied first with the 'everyday' clock synchronization, with the corresponding absolute simultaneity, time dilation and space contraction, introducing the Lorentz transformation only at a posterior phase.

In the line of Bell and Leubner, we suggest that special relativity should be taught under a weak formulation of both postulates, as their standard form contains additional assumptions to those implied by experiment. As a matter of fact, each of the postulates may be formulated in more general terms, while remaining fully consistent with all available observations. Our analysis starts with the postulate of the constancy of the speed of light. Based on experiment, and on the conceptualization of time [1], we write it as

- the two-way speed of light in empty space is $c$ in any inertial frame, independently of the velocity of the source emitting the light.

In addition, we define the rest system as

- the system in which the one-way speed of light in empty space is $c$ in any direction, independently of the velocity of the source emitting the light.

To start the study of special relativity, no assertions about the possible uniqueness of this frame are required. It is assumed one such frame exists, and what happens with the others follows subsequently in a natural way.

With this first postulate and the definition of the rest system, the phenomena of time dilation and space contraction can be obtained in the usual way, as outlined in [2]. Moreover, the IST transformation, relating the coordinates of any event in the rest system to those of another inertial frame, is immediately deduced without any effort.

In our opinion, the principle of relativity should be introduced only at a later stage, after studying the standard relativistic effects with the IST transformation, as an erroneous interpretation of its meaning may impose a too limiting framework from the beginning. Specifically, a too strong formulation of the principle of relativity induces the idea that no other transformation of coordinates is acceptable except the Lorentz transformation. In fact, no one starts a discussion on Newtonian dynamics by introducing a set of transformations under which it is invariant. Similarly, the Lorentz transformations are somewhat secondary to an understanding of special relativity.

We formulate the principle of relativity in the same way as Feynman [4],

- all the experiments performed in a closed cabin in vacuum in any moving inertial frame will appear the same as if performed in the rest system, provided, of course, that one does not look outside.

It is then possible to make the Lorentz transformation emerge naturally. Its important role becomes evident, but not ‘mythical’, since it is clear already that other coordinate transformations can be used as well. The invariance in the form of the laws of physics under a Lorentz transformation can then be associated with the principle of relativity, in the line of the second formulation by Feynman,

- all laws of physics, when written with Lorentzian coordinates, keep the same form in all inertial frames, the same as in the rest system.

The step to 4D geometry is then very simple to do, as is the idea that physics and its laws do not depend on the coordinates chosen, i.e., on the choice we made to *describe* the phenomena. In particular, we can set or ‘synchronize’ our own clocks as it most pleases us, but reality is not changed by the way the clocks have been set.

This remark opens the door to a discussion of the conventionality of simultaneity thesis that we believe should be part of any course on special relativity. We cannot address the subject here, but it is amply documented in the literature. The first reflections related to the conventionality of simultaneity date back to Poincaré, although the origins of the conventionalism thesis are attributed to Hans Reichenbach, with its two books in 1924 and 1928 [29, 30]. Einstein contributed to the discussion in several letters and books. The subject keeps attracting the interest of physicists and philosophers, and further important insight has been given, just to name a few, by Eddington [22], Edwards [11], Malament [31], Brehme [32], Ungar [33], Capria [34], Minguzzi [35], Szabó [21], Martínez [36] and Macdonald [37]. The short paper by Martínez or the longer one by Capria contain a very good review of the arguments involved. We subscribe to the views of Capria and resolutely oppose the ideas of the strong ‘conventionality’ thesis and of ‘operationalism’. According to this view, only directly measurable quantities have a physical meaning, the others can *only* be ‘determined’ or ‘stipulated’ by human convention. In contrast, we find it obvious that the one-way speed of light does exist, even if we cannot measure it. We sustain that reality is not changed by the ‘convention’ adopted: the convention only assigns a *name* to a *concept*, and the same name, for example ‘speed’, can be given to different notions.

The meaning of speed does not disappear simply because we do not know how to measure it: it is the distance divided by the ‘time of the journey’. We admit the following questions: what is the time of the journey? What is the speed of light? The two interrogations are of course interconnected, and rely on the determination of the ‘common time’ of the clocks. And the latter question cannot be answered by stating by decree it is $c$, its measured two-way value. This can hardly be seen as an answer. What can be done is to admit that there is an indetermination: we do not know.

It follows that special relativity is incomplete and undetermined unless one really knows the one-way speed of light or, which is the same, unless the rest system has been unambiguously identified by an internal measurement. One solution to this deadlock is to introduce a novel concept—the Einstein speed—and for practical purposes treat the one-way speed of light as if its value was $c$. This corresponds to an operational procedure to study relative motion without any reference to absolute motion. In this methodology, the knowledge of the value of the one-way speed of light is superfluous.

Clearly, the dominant attitude underlaying physics education nowadays may tend to argue as follows: if the general theory herein presented is undetermined, its concepts can be considered as useless and the theory is irrelevant to physics; we can simply rename the notion of 'Einstein speed' as 'speed' and forget the rest. Apart from the statement opening the present section and from the points raised by Bell, Leubner and Selleri [6–8], for instance, we would like to emphasize two additional issues.

First, many scientists are still not aware that Einstein's special relativity is fully compatible with the assumption of a preferred frame. It is not a question that they find this assumption does not bring anything new to the study of physics, it is that they find it contradicts special relativity.

Second, even if someone may stick with the opinion that the formulation herein suggested 'does not bring anything new to physics', we claim it gives additional background that can be kept in mind and help the analysis of new ideas and experiments that may appear in the future. One such example is given by the recent proposals by Cahill [38, 39] and by Consoli and Costanzo [40, 41]. They allege that old and new interferometer experiments of the Michelson–Morley type in a rarefied gas provide an internal detection of absolute motion consistent with the one obtained by 'looking outside'. To enter the discussion around this somewhat polemic topic goes far beyond the purpose of the present paper. Nonetheless, the main hypothesis supporting their claims are briefly reviewed in [19], where an experiment capable of confirming or refuting their ideas was proposed. A much simpler variant of this experiment was also devised very recently [42].

## Acknowledgments

We are indebted to Professors Gianfranco Spavieri, Zbigniew Oziewicz, Jan Czerniawski and Bernhard Rothenstein for very rich and fruitful discussions.

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